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Proton angular distributions from the reaction $N^{14}(d,p)N^{15}$

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With 6 figures in the text

Introduction

In the reaction $N^{14}(d,p)N^{15}$ the angular distributions of the proton groups leading to the two lowest excited levels in N^{15}, at 5.276 ± 0.006 and 5.305 ± 0.006 MeV, have first been resolved by Sharp and Sperduto [1]. Their measurements were made at a deuteron bombarding energy of 7 MeV. At this energy, the proton group to the 5.276 MeV level showed a stripping distribution with $l_n = 2$, superimposed on an isotropic background, while that to the 5.305 MeV level showed a relatively isotropic distribution.

In our case a bombarding energy of 0.8 MeV is used for an angular distribution study of these groups. It is interesting to see to what extent an interpretation of our results based on a non-Coulomb stripping theory gives the same results as were obtained in [1]. If the results differ, some conclusions might be possible as to the relative importance of various reaction mechanisms at low and high deuteron energy compared to the Coulomb barrier.

Experimental apparatus and procedure

The 800 keV deuterons from the Nobel Institute Cockcroft–Walton accelerator were used to bombard thin adenine ($C_5N_5H_5$) targets, evaporated on Al-foils of 0.15 mg/cm². The proton groups from the $N^{14}(d,p)N^{15}$ reaction were analysed with the rotatory double-focusing heavy-particle spectrometer and detected in nuclear emulsion plates (Ilford C2, 50 μ). For further data concerning the equipment and the experimental procedure in general we refer to [2], [3] and [4].

The two proton groups were always detected in the same plate. Exposures were made at every 7.5° between laboratory angles $\theta_l = 4.5°$ and 132.4° and the differential cross-section for a certain angle was experimentally related to the cross-section for a reference angle by the procedure of several alternating exposures which has been described earlier. The deuteron bombardment of the target was 400–800 μC for each plate exposed and the current density was kept low, about 0.1 μA/mm², in order to spare the evaporated target layer.

For angles θ_l below 40°, the target was placed in such a way that the spectrometer accepted protons which had traversed the Al-foil.

Figs. 1 and 2 show the momentum prophiles of protons obtained in one backward and one forward angle θ_l. The two peaks, whose Q-values differ by only about 30 keV,

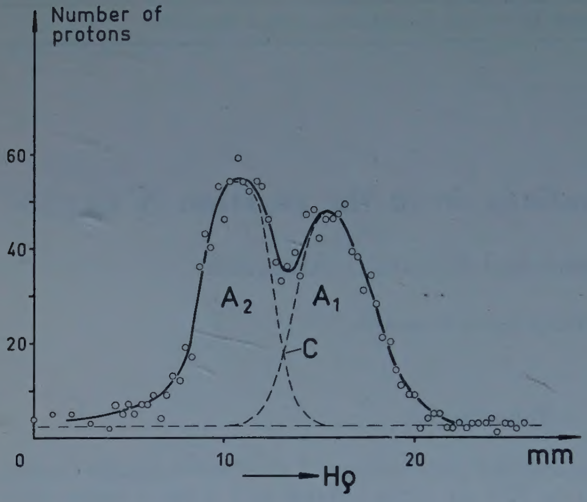

Fig. 1. Spectrum of protons from $N^{14}(d,p)N^{15}$, Q_1 and Q_2, obtained by counting number of tracks per 0.25 mm strip in a nuclear emulsion plate at $\theta_l = 4.5°$. $E_d = 0.8$ MeV.

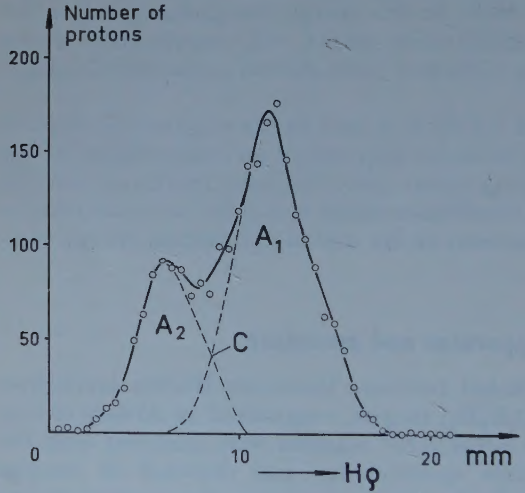

Fig. 2. Spectrum of protons from $N^{14}(d,p)N^{15}$, Q_1 and Q_2, at $\theta_l =$ 110.9°. $E_d = 0.8$ MeV.

are in no angle fully resolved and one has to make an adequate dividing of the double peak into its components A_1 and A_2 in order to get the independent angular distributions of the two groups. After every run we have got two plates exposed, which each gives a prophile like the one in e.g. Fig. 1. One plate gives the areas $A_1(\theta_l)$ and $A_2(\theta_l)$ and also their sum $A(\theta_l) = A_1(\theta_l) + A_2(\theta_l)$ for the angle θ_l, while the other plate gives the same quantities for a reference angle, e.g. 90°. As all the curves are not resolved well enough to give good values of A_1 and A_2, we use some of them to get a value of A only. A good use of the complete experimental material is then made by first calculating the ratios $A_1(\theta_l)/A_2(\theta_l) = k(\theta_l)$ and $A(\theta_l)/A(90°)$ for various values of θ_l. The angular distributions of the two groups are then obtained as:

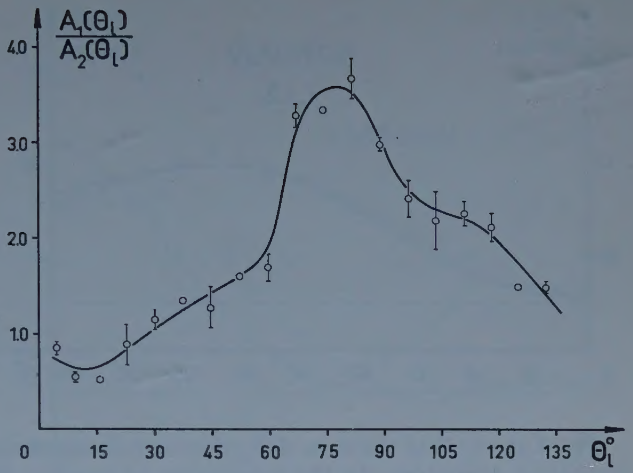

Fig. 3. Ratio between the areas of the two proton peaks $A_1(\theta_l)$ and $A_2(\theta_l)$ as a function of θ_l. The errors which were computed as described in the text are indicated at points which are a mean value of several different runs.

$$\frac{A_1(\theta_l)}{A_1(90^\circ)} = \frac{A(\theta_l)}{A(90^\circ)} \cdot \frac{1+k(90^\circ)}{1+k(\theta_l)} \cdot \frac{k(\theta_l)}{k(90^\circ)}, \tag{1}$$

$$\frac{A_2(\theta_l)}{A_2(90^\circ)} = \frac{A(\theta_l)}{A(90^\circ)} \cdot \frac{1+k(90^\circ)}{1+k(\theta_l)}. \tag{2}$$

Fig. 3 shows $k(\theta_l) = A_1(\theta_l)/A_2(\theta_l)$ for various θ_l. We see that for $\theta_l < 30^\circ$, A_2 is bigger than A_1, but for all other angles A_1 is the dominant peak. Therefore A_2 is generally more sensitive to the uncertainty associated with the dividing of A into its two components. This will also be apparent as a bigger error in the angular distribution $A_2(\theta_l)/A_2(90^\circ)$ than in $A_1(\theta_l)/A_1(90^\circ)$.

The limits of error shown in Fig. 3 are relative errors, indicated at points which are averages of several independent runs. A method of weighing the various values contributing to the average has been used which considers (*a*) the statistical accuracy, i.e. the total number of proton tracks in the primary peaks, (*b*) the overlapping of the two peaks and (*c*) the relative sensitivity of the ratio $k(\theta_l)$ to a displacement of the crossing point C.

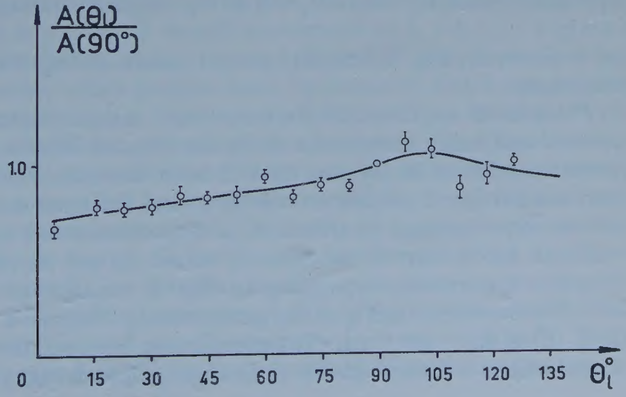

Fig. 4. The total area $A(\theta_l) = A_1(\theta_l) + A_2(\theta_l)$ as a function of θ_l. The statistical deviation of each point is shown.

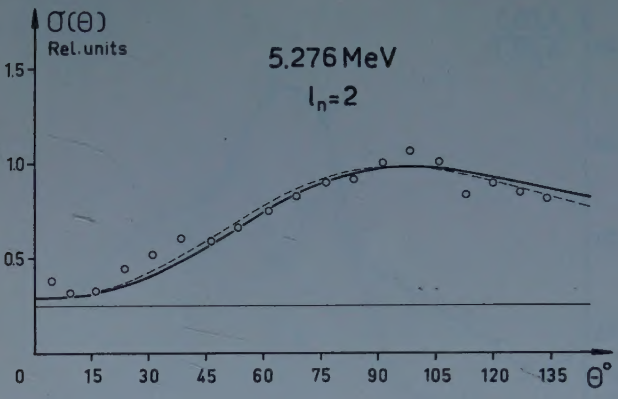

Fig. 5. Angular distribution of the $N^{14}(d,p)N^{15}$ proton group leading to the 5.276 MeV level in N^{15}. $E_d = 0.8$ MeV. The curves corresponding to $l_n = 2$ are superimposed on an isotropic background. Solid line: Butler theory, $r_0 = 5.1 \times 10^{-13}$ cm. Broken line: Bhatia *et al.* theory $R = 6.2 \times 10^{-13}$ cm. Fine line isotropic background.

Fig. 4 shows that the sum $A(\theta_l)$ does not change much with θ_l. The errors are the statistical deviations. In the calculation of angular distributions according to (1) and (2) we have used the individual data points of Figs. 3 and 4. The solid curves in these figures were drawn only to make the diagrams easier to survey. To obtain the angular distributions in the centre of mass-system, (1) and (2) have been multiplied by the proper solid-angle factors before the final results have been given.

Results and discussion

Figs. 5 and 6 show the two observed angular distributions. The distribution of the first group (5.276 MeV) has a broad maximum at about 100° and that of the other (5.305 MeV) a characteristic minimum at about 80°. We have desisted from indicating any errors in these figures, as they were very difficult to estimate. The reason that we get much more accurate results in Fig. 5 than in Fig. 6 has already been given.

For each distribution, a function fitted to the experimental points was evaluated in a series of Legendre polynomials of the first kind. So many terms were included as seemed reasonable with respect to the spread of the points. The functions are:

$$I_1 = 0.80 - 0.14\,P_1 - 0.36\,P_2 + 0.04\,P_3 - 0.08\,P_6 \quad \text{(5.276 MeV group)}, \qquad (3)$$

$$I_2 = 1.47 - 0.36\,P_1 + 0.81\,P_2 + 0.10\,P_3 - 0.17\,P_4 - 0.08\,P_5 \quad \text{(5.305 MeV group)}. \qquad (4)$$

(4) is shown in Fig. 6, but (3) was not drawn in Fig. 5 to avoid making that diagram indistinct.

Theoretical angular distributions were calculated assuming a deuteron stripping process and using the results of Butler [5] and Bhatia *et al.* [6]. The same deuteron wave function as in [5] was used in both theories. From Fig. 5 in which theoretical curves with $l_n = 2$ are drawn it is seen that the agreement is good if an isotropic part of the experimental distribution is first subtracted (about 25 % of the maximum value at 100°). Curves for other l_n values do not fit the experimental points at all. The $l_n = 1$ curve corresponding to Fig. 5 would thus have its maximum at about 50°. For the curves in Fig. 5 the parameter r_0 of [5] is 5.1×10^{-13} cm and the parameter R of [6] is 6.2×10^{-13} cm. The comparison between the experimental and theoretical distributions with reasonable radii thus proposes that deuteron stripping takes place

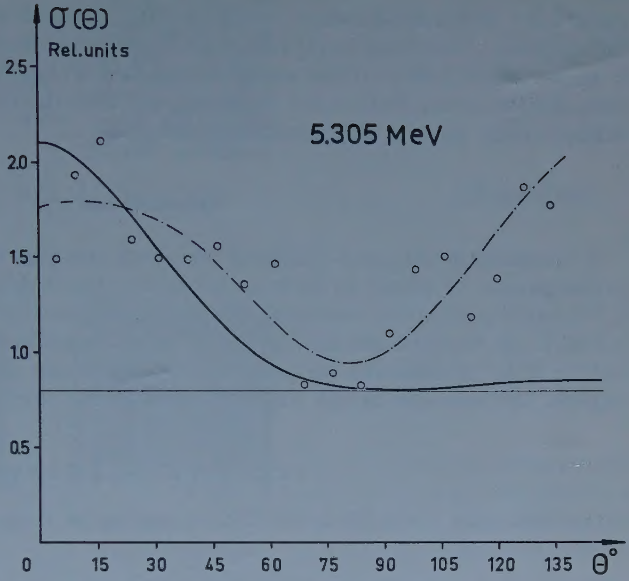

Fig. 6. Angular distribution of the $N^{14}(d,p)N^{15}$ proton group leading to the 5.305 MeV level in N^{15}. $E_d = 0.8$ MeV. The theoretical curve (solid) is calculated with Butlers theory, $r_0 = 5.1 \times 10^{-13}$ cm, $l_n = 0$. The fine line shows the isotropic background assumed. Dash-dotted line: Legendre polynomial according to equation (4).

with $l_n = 2$. This is in agreement with the result of [1] at a deuteron energy of 7 MeV where a best fit was achieved for $r_0 = 5.5 \times 10^{-13}$ cm and about 55 % isotropic background. It is interesting to find that deuteron stripping probably takes place to a dominant extent also at our low energy $E_d = 0.8$ MeV. $l_n = 2$ means that the parity of the 5.276 MeV level is positive and the spin is 1/2, 3/2, 5/2 or 7/2. From calculations of the positive parity levels in N^{15} a spin of 5/2 is suggested [7] when the levels are regarded to belong to configurations $(1s)^4(1p)^{10}\,2s + (1s)^4\,(1p)^{10}\,1d + (1s)^3\,(1p)^{12}$ and the interaction is described by a two-body central plus a one-body spin-orbit potential.

As to the 5.305 MeV group, Fig. 6 shows undoubtedly that the distribution has a minimum. In [1] is concluded that no stripping takes place at 7 MeV. However, the distribution in [1] also seems to have a slight minimum. In Fig. 6 we have drawn a Butler curve with $l_n = 0$, $r_0 = 5.1 \times 10^{-13}$ cm and an isotropic background nearly as high as the minimum of the experimental curve. It is seen that if a small contribution from deuteron stripping is present it should correspond to $l_n = 0$ ($l_n = 1$ gives a curve with its maximum at about 50°). If $l_n = 0$ the parity of the state is positive and the spin is 1/2 or 3/2. Then some other process must be assumed which can explain the increase in $\sigma(\theta)$ for backward angles. In the case of the reaction $B^{11}(d,n)C^{12}$ the angular distribution of the ground state group is similar to that of Fig. 6 for deuteron energies in the range 3–5 MeV. To explain these distributions an interaction consisting of a deuteron stripping plus a so-called heavy particle stripping has been assumed [8] and thereby a good agreement is obtained. Deuteron stripping was then seen to be favoured by low deuteron energy. If such a combined mechanism would be responsible in our case, one would be tempted to expect a greater anisotropy in [1] than observed. However, it should be interesting to know the angular distribution for intermediate deuteron energies and also for energies less than 0.8 MeV. From theoretical reasons it was suggested in [7] that the 5.305 MeV level has the assignment 1/2+ and a small reduced width for $l_n = 0$ which would give a small probability for stripping. According to [1] Lane has suggested that the width for neutron breakup is zero—which follows if the configuration is $(1s)^3(1p)^{12}$—and that therefore no stripping should occur. This is not in agreement with the result of [7], that the $(1s)^3(1p)^{12}$ configuration gives a very small contribution.

Conclusions

A comparison with non-Coulomb stripping theories has been made in the present investigation. It seems to be most probable that a deuteron stripping process with $l_n = 2$ takes part in the reaction giving the group to the 5.276 MeV level also at $E_d = 0.8$ MeV. As to the 5.305 MeV group it cannot be excluded that there is a small contribution of $l_n = 0$ deuteron stripping. Perhaps another kind of direct interaction might explain the increase in the angular distribution curve for $\theta > 80°$.

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